PART OF THE SUPERVISORY CONTROLLER FOR THE OISTERWIJKSEBAAN-BRIDGE SPLC

FERDIE F.H. REIJNEN, TOBY R. ERENS, JOANNA M. VAN DE MORTEL-FRONCZAK,
AND JACOBUS E. ROODA

In this document, an example is provided regarding the splitting of a supervisor for implementation on a safety PLC. For this, part of the supervisor for the Oisterwijksebaan bridge, located in Tilburg, The Netherland, is described. The plant consists of 14 components, modeled with finite automata (FAs) and Boolean input variables (BIVs) and there are 28 event-condition requirements. In Section 1 the case is described. Subsequently, in Section 2, the splitting is performed. In the appendix, a list of symbols and the implementation code is provided.

1. The Oisterwijksebaan bridge case

Figure. 1 shows a sketch of the Oisterwijksebaan-bridge. This is a rotating bridge that can be opened whenever vessels want to pass. The bridge consists of the following components: two stop signs SS1 and SS2, two boom barriers BB1 and BB2, two boom barrier lights BL1 and BL2, and a bridge deck BD. Additionally, a graphical user interface is present, allowing an operator to send commands to the bridge. In the remainder of this section, the component models are provided

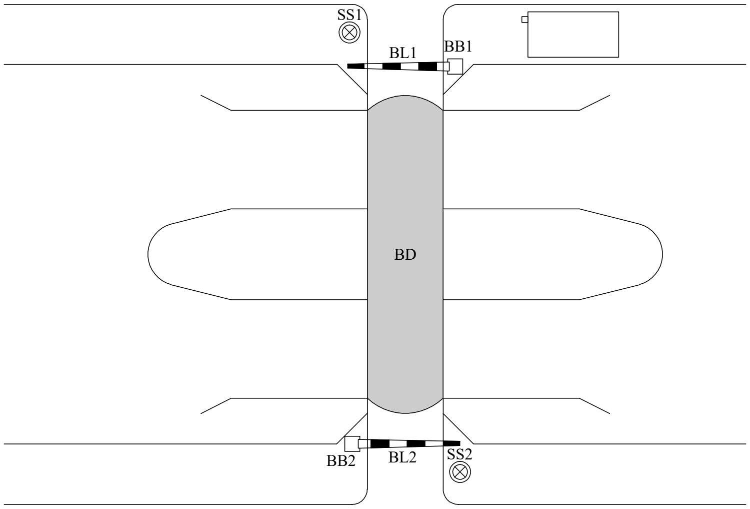


Figure 1. Oisterwijksebaan-bridge.

Figure 2 shows the model of the actuator that enables both stop signs simultaneously. Both stop signs have a sensor that measures whether the lamp is activated. These sensors are represented by two BIVs: `S_SS1_On` and `S_SS2_On`.

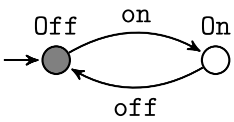


FIGURE 2. Stop sign actuator P_{SS}.

Each boom barrier consists of a bidirectional actuator, shown in Figure 3. Each boom barrier has two sensors that measure whether the barrier is fully closed or fully open. These sensors are represented by BIVs: `S_BB1_Open`, `S_BB1_Closed`, `S_BB2_Open`, and `S_BB2_Open`.

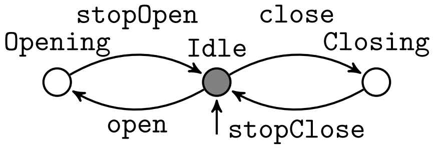


FIGURE 3. Boom barrier actuator $P_{\mathrm{BB}X}, X \in \{1, 2\}$.

Each boom barrier contains a light BL. One actuator enables both lights simultaneously, shown in Figure 4. Each light has a sensor that measures whether the lamp is activated. These sensors are represent by two BIVs: `S_BL1_On` and `S_BL2_On`.

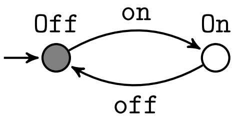


FIGURE 4. Barrier light actuator P_{BL}.

The bridge deck consists of a bidirectional actuator, shown in Figure 5. The bridge deck has two sensors that measure when it is fully closed or fully open. These sensors are represented by two BIVs: `S_BD_Open` and `S_BD_Closed`.

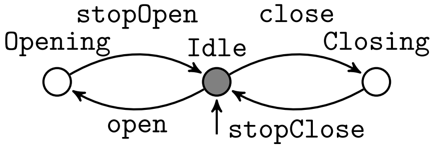


FIGURE 5. Bridge deck actuator P_{BD}.

Lastly, there is a GUI present, shown in Figure 6. A command (via a mouse click) is modeled as an uncontrollable event. Whenever a command activates an action, a controllable event represents that action being completed. The possible commands are: stopping land traffic, releasing land traffic, closing the barriers, opening the barriers, opening the bridge, and closing the bridge.

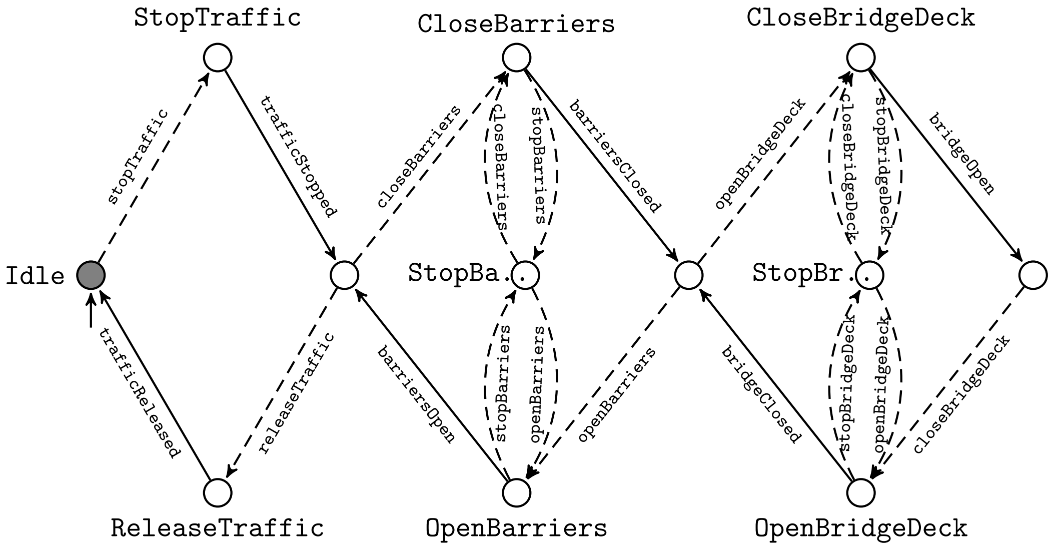


FIGURE 6. GUI P_{GUI}.

The components are connected to the variables in the output image of the PLC, via a hardware mapping. The hardware mapping is shown in Table 1. For each output image variable, one event is defined for setting the value to **T** and one event for setting the value to **F**.

TABLE 1. Hardware mapping of the actuators T_Q.

Output image variable	Event for **T**	Event for **F**
q_{stopsign}	P_{SS}.on	P_{SS}.off
q_{bb1Open}	P_{BB1}.open	P_{BB1}.stopOpen
q_{bb1Close}	P_{BB1}.close	P_{BB1}.stopClose
q_{bb2Open}	P_{BB2}.open	P_{BB2}.stopOpen
q_{bb2Close}	P_{BB2}.close	P_{BB2}.stopClose
$q_{\text{barrierlight}}$	P_{BL}.on	P_{BL}.off
$q_{\text{bridgeOpen}}$	P_{BD}.open	P_{BD}.stopOpen
$q_{\text{bridgeClose}}$	P_{BD}.close	P_{BD}.stopClose

Tables 2 and 3 show the regular requirements $\mathcal{R}'_{\text{R}}$ and the safety requirements $\mathcal{R}'_{\text{S}}$, respectively. The portioning is based on as risk assessment study, conducted by safety experts.

Table 2. Regular requirements $\mathcal{R}'_{\mathrm{R}}$.

	Event name	Condition
R1	$P_{\mathrm{GUI}}.\mathtt{trafficStopped}$	$\mathtt{S\_SS1\_On} \wedge \mathtt{S\_SS2\_On}$
R2	$P_{\mathrm{GUI}}.\mathtt{trafficReleased}$	$\neg\mathtt{S\_SS1\_On} \wedge \neg\mathtt{S\_SS2\_On}$
R3	$P_{\mathrm{GUI}}.\mathtt{barriersClosed}$	$\mathtt{S\_BB1\_Closed} \wedge \mathtt{S\_BB2\_Closed}$
R4	$P_{\mathrm{GUI}}.\mathtt{barriersOpen}$	$\mathtt{S\_BB1\_Open} \wedge \mathtt{S\_BB2\_Open}$
R5	$P_{\mathrm{GUI}}.\mathtt{bridgeOpen}$	$\mathtt{S\_BD\_Open}$
R6	$P_{\mathrm{GUI}}.\mathtt{bridgeClosed}$	$\mathtt{S\_BD\_Closed}$
R7	$P_{\mathrm{SS}}.\mathtt{on}$	$P_{\mathrm{GUI}}.\mathtt{StopTraffic}$
R8	$P_{\mathrm{SS}}.\mathtt{off}$	$P_{\mathrm{GUI}}.\mathtt{ReleaseTraffic}$
R9	$P_{\mathrm{BB1}}.\mathtt{open}$	$P_{\mathrm{GUI}}.\mathtt{OpenBarriers}$
R10	$P_{\mathrm{BB1}}.\mathtt{close}$	$P_{\mathrm{GUI}}.\mathtt{CloseBarriers}$
R11	$P_{\mathrm{BB1}}.\mathtt{stopOpen}$	$P_{\mathrm{GUI}}.\mathtt{StopBarriers} \vee \mathtt{S\_BB1\_Open}$
R12	$P_{\mathrm{BB1}}.\mathtt{stopClose}$	$P_{\mathrm{GUI}}.\mathtt{StopBarriers} \vee \mathtt{S\_BB1\_Closed}$
R13	$P_{\mathrm{BB2}}.\mathtt{open}$	$P_{\mathrm{GUI}}.\mathtt{OpenBarriers}$
R14	$P_{\mathrm{BB2}}.\mathtt{close}$	$P_{\mathrm{GUI}}.\mathtt{CloseBarriers}$
R15	$P_{\mathrm{BB2}}.\mathtt{stopOpen}$	$P_{\mathrm{GUI}}.\mathtt{StopBarriers} \vee \mathtt{S\_BB2\_Open}$
R16	$P_{\mathrm{BB2}}.\mathtt{stopClose}$	$P_{\mathrm{GUI}}.\mathtt{StopBarriers} \vee \mathtt{S\_BB2\_Closed}$
R17	$P_{\mathrm{BL}}.\mathtt{on}$	$P_{\mathrm{GUI}}.\mathtt{StopTraffic}$
R18	$P_{\mathrm{BL}}.\mathtt{off}$	$P_{\mathrm{GUI}}.\mathtt{ReleaseTraffic}$
R19	$P_{\mathrm{BD}}.\mathtt{open}$	$P_{\mathrm{GUI}}.\mathtt{OpenBridgeDeck}$
R20	$P_{\mathrm{BD}}.\mathtt{close}$	$P_{\mathrm{GUI}}.\mathtt{CloseBridgeDeck}$
R21	$P_{\mathrm{BD}}.\mathtt{stopOpen}$	$P_{\mathrm{GUI}}.\mathtt{StopBridgeDeck} \vee \mathtt{S\_BD\_Open}$
R22	$P_{\mathrm{BD}}.\mathtt{stopClose}$	$P_{\mathrm{GUI}}.\mathtt{StopBridgeDeck} \vee \mathtt{S\_BD\_Closed}$

Table 3. Safety requirements $\mathcal{R}'_{\mathrm{S}}$.

	Event name	Condition
R23	$P_{\mathrm{SS}}.\mathtt{off}$	$\mathtt{S\_BB1\_Open} \wedge \mathtt{S\_BB2\_Open}$
R24	$P_{\mathrm{BB1}}.\mathtt{open}$	$\mathtt{S\_BD\_Closed}$
R25	$P_{\mathrm{BB1}}.\mathtt{close}$	$\mathtt{S\_SS1\_On} \wedge \mathtt{S\_SS2\_On}$
R26	$P_{\mathrm{BB2}}.\mathtt{open}$	$\mathtt{S\_BD\_Closed}$
R27	$P_{\mathrm{BB2}}.\mathtt{close}$	$\mathtt{S\_SS1\_On} \wedge \mathtt{S\_SS2\_On}$
R28	$P_{\mathrm{BD}}.\mathtt{open}$	$\mathtt{S\_BB1\_Closed} \wedge \mathtt{S\_BB2\_Closed}$

When performing supervisor synthesis, it has shown that the plant in combination with the requirements is safe, nonblocking, controllable, and maximally permissive.

2. Splitting the supervisor

In this section, the method as described in Section 4.2 of the paper is followed. The steps are as follows.

(a) It is verified that the plant is a product system and that the condition given in Eq. 3 holds, i.e., all safety requirements depend on BIVs.

(b) Sets I_{S} and I_{R} are derived (Eqs. 4 and 5):

$$\begin{aligned} I_{\mathrm{S}} &= \{\mathtt{S\_SS1\_On}, \mathtt{S\_SS2\_On}, \mathtt{S\_BB1\_Open}, \mathtt{S\_BB1\_Closed}, \\ &\quad \mathtt{S\_BB2\_Open}, \mathtt{S\_BB2\_Closed}, \mathtt{S\_BD\_Closed}\} \\ I_{\mathrm{R}} &= \{\mathtt{S\_BL1\_On}, \mathtt{S\_BL2\_On}, \mathtt{S\_BD\_Open}\} \end{aligned}$$

(c) Sets Q_{S} and Q_{R} are derived (Eqs. 6 and 7).

$$\begin{aligned} Q_{\mathrm{S}} &= \{q_{\mathrm{stopsign}}, q_{\mathrm{bb1Open}}, q_{\mathrm{bb1Close}}, q_{\mathrm{bb2Open}}, q_{\mathrm{bb2Close}}, q_{\mathrm{bridgeOpen}}\} \\ Q_{\mathrm{R}} &= \{q_{\mathrm{barrierlight}}, q_{\mathrm{bridgeClose}}\} \end{aligned}$$

(d) Sets $\mathcal{P}_{\mathrm{S}}$ and $\mathcal{P}_{\mathrm{R}}$ are derived (Eqs. 8 and 9).

$$\begin{aligned} \mathcal{P}_{\mathrm{S}} &= \{P_{\mathrm{SS}}, P_{\mathrm{BB1}}, P_{\mathrm{BB2}}, P_{\mathrm{BD}}\} \\ \mathcal{P}_{\mathrm{R}} &= \{P_{\mathrm{GUI}}, P_{\mathrm{BL}}\} \end{aligned}$$

(e) Sets Σ_{S} and Σ_{R} are derived (Eqs. 10 and 11). These events are simply the events belonging to the safety and regular components above.

(f) Regular requirement set $\mathcal{R}'_{\mathrm{R}}$ is split (Eqs. 12 and 13).

$$\begin{aligned} \mathcal{R}^{\mathrm{S}}_{\mathrm{R}} &= \{\text{R7, R8, R9, R10, R11, R12, R13, R14, R15, R16, R19, R20, R21, R22}\} \\ \mathcal{R}^{\mathrm{R}}_{\mathrm{R}} &= \{\text{R1, R2, R3, R4, R5, R6, R17, R18}\} \end{aligned}$$

(g) Regular requirement set for the safety events $\mathcal{R}^{\mathrm{S}}_{\mathrm{R}}$ is split (Eqs. 14 and 15).

$$\begin{aligned} \mathcal{R}^{\mathrm{SS}}_{\mathrm{R}} &= \{\text{R11, R12, R15, R16, R21, R22}\} \\ \mathcal{R}^{\mathrm{SR}}_{\mathrm{R}} &= \{\text{R7, R8, R9, R10, R13, R14, R19, R20}\} \end{aligned}$$

(h) Requirements in $\mathcal{R}^{\mathrm{SR}}_{\mathrm{R}}$ are merged (Eq. 16). The result is given in Table 4.

Table 4. R2S communication.

Variable name	Condition
$c_{\mathtt{stopsign\_on}}$	$P_{\mathrm{GUI}}.\mathtt{StopTraffic}$
$c_{\mathtt{stopsign\_off}}$	$P_{\mathrm{GUI}}.\mathtt{ReleaseTraffic}$
$c_{\mathtt{boombarrier1\_open}}$	$P_{\mathrm{GUI}}.\mathtt{OpenBarriers}$
$c_{\mathtt{boombarrier1\_close}}$	$P_{\mathrm{GUI}}.\mathtt{CloseBarriers}$
$c_{\mathtt{boombarrier2\_open}}$	$P_{\mathrm{GUI}}.\mathtt{OpenBarriers}$
$c_{\mathtt{boombarrier2\_close}}$	$P_{\mathrm{GUI}}.\mathtt{CloseBarriers}$
$c_{\mathtt{bridge\_open}}$	$P_{\mathrm{GUI}}.\mathtt{OpenBridgeDeck}$
$c_{\mathtt{bridge\_close}}$	$P_{\mathrm{GUI}}.\mathtt{CloseBridgeDeck}$

(i) Requirement set $\mathcal{R}_D$ is added, Table 5 (Eq. 17).

Table 5. $\mathcal{R}_D$ requirements.

	Event name	Condition
R29	$P_{\mathrm{SS}}.\mathtt{on}$	$v_{\mathtt{stopsign\_on}}$
R30	$P_{\mathrm{SS}}.\mathtt{off}$	$v_{\mathtt{stopsign\_off}}$
R31	$P_{\mathrm{BB1}}.\mathtt{open}$	$v_{\mathtt{boombarrier1\_open}}$
R32	$P_{\mathrm{BB1}}.\mathtt{close}$	$v_{\mathtt{boombarrier1\_close}}$
R33	$P_{\mathrm{BB2}}.\mathtt{open}$	$v_{\mathtt{boombarrier2\_open}}$
R34	$P_{\mathrm{BB2}}.\mathtt{close}$	$v_{\mathtt{boombarrier2\_close}}$
R35	$P_{\mathrm{BD}}.\mathtt{open}$	$v_{\mathtt{bridge\_open}}$
R36	$P_{\mathrm{BD}}.\mathtt{close}$	$v_{\mathtt{bridge\_close}}$

(j) The requirements in the safety part and in the regular part are (Eqs. 18 and 19):

$$\mathcal{R}_{\mathrm{S}} = \{\mathrm{R11, R12, R15, R16, R21, R22, R23, R24, R25, R26, R27, R28, R29, R30, R31,} \\ \mathrm{R32, R33, R34, R35, R36}\}$$

$$\mathcal{R}_{\mathrm{R}} = \{\mathrm{R7, R8, R9, R10, R13, R14, R19, R20}\}$$

(k) The variables that have to be communicated are derived (Eqs. 20 and 21). There are no variables that have to be communicated via D_{S}. The variables that are communicated via D_{R} are:

$$D_{\mathrm{R}} = \{v_{\mathtt{stopsign\_on}}, v_{\mathtt{stopsign\_off}}, v_{\mathtt{boombarrier1\_open}}, v_{\mathtt{boombarrier1\_close}} \\ v_{\mathtt{boombarrier2\_open}}, v_{\mathtt{boombarrier2\_close}}, v_{\mathtt{bridge\_open}}, v_{\mathtt{bridge\_close}} \\ P_{\mathrm{GUI}}.\mathtt{StopBarriers}, P_{\mathrm{GUI}}.\mathtt{StopBridgeDeck}\}$$

Appendix A. List of symbols

Model symbols

$\mathcal{P}$	Plant model
$\mathcal{R}$	Requirements model
Σ	Events
c	Condition
i	Boolean input variable
L	Locations
P	Component model
R	Event-condition requirement
T_Q	Hardware mapping
v_l	Location reference

Split symbols

Σ_R	Set of events in the regular part
Σ_S	Set of events in the safety part
D_R	Set of regular data buffer variables
D_S	Set of safety data buffer variables
I_R	Set of regular input image variables
I_S	Set of safety input image variables
Q_R	Set of regular output image variables
Q_S	Set of safety output image variables
$\mathcal{R}_D$	Set of requirements via communication
$\mathcal{R}_\mathrm{R}$	Set of requirements in the regular part
$\mathcal{R}_\mathrm{S}$	Set of requirements in the safety part
$\mathcal{R}'_\mathrm{R}$	Set of regular requirements
$\mathcal{R}_\mathrm{R}^\mathrm{R}$	Set of regular requirements for Σ_R
$\mathcal{R}_\mathrm{R}^\mathrm{S}$	Set of regular requirements for Σ_S
$\mathcal{R}_\mathrm{R}^\mathrm{SR}$	Set of regular requirements for Σ_S in the regular part
$\mathcal{R}_\mathrm{R}^\mathrm{SS}$	Set of regular requirements for Σ_S in the safety part
$\mathcal{R}'_\mathrm{S}$	Set of safety requirements
S	Supervisor
c_σ	Regular condition for event σ
v_σ	Evaluation result of c_σ

Appendix B. SPLC implementation code

In this section, the function block diagrams (FBDs) implemented in the safety part of the PLC are given. First, the stopsign FBDs are given, then the barrier FBDs, and lastly the bridge FBDs. Here, the FBDs are implemented in TIA Portal Version 15 from Siemens.

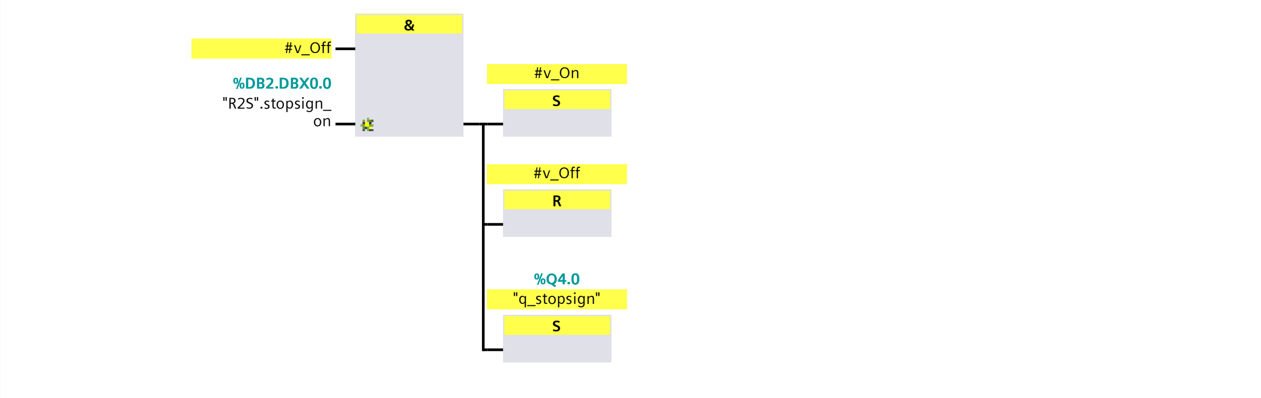
WODES / PLC_1 [CPU 315F-2 PN/DP] / Program blocks

stopsign [FB2]

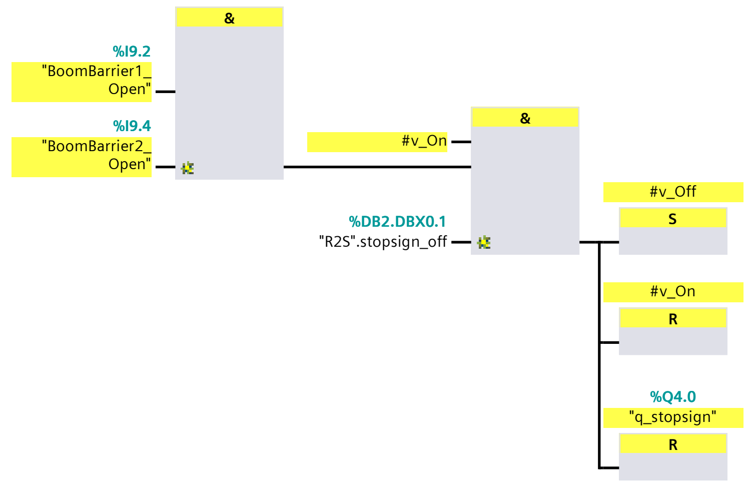
stopsign Properties					
General					
Name	stopsign	**Number**	2	**Type**	FB
Language	FBD	**Numbering**	Automatic		
Information					
Title		**Author**		**Comment**	
Family		**Version**	0.1	**User-defined ID**	

Block_1									
Name	**Data type**	**Offset**	**Default value**	**Accessible from HMI/OPC UA**	**Writable from HMI/OPC UA**	**Visible in HMI engineering**	**Setpoint**	**Supervision**	**Comment**
Input									
Output									
InOut									
▼ Static									
v_Off	Bool	0.0	true	True	True	True	False		
v_On	Bool	0.1	false	True	True	True	False		
Temp									
Constant									

Network 1: on



Network 2: off


&
%I9.2
"BoomBarrier1_
Open"
%I9.4
"BoomBarrier2_
Open"
&
#v_On
%DB2.DBX0.1
"R2S".stopsign_off
#v_Off
S
#v_On
R
%Q4.0
"q_stopsign"
R

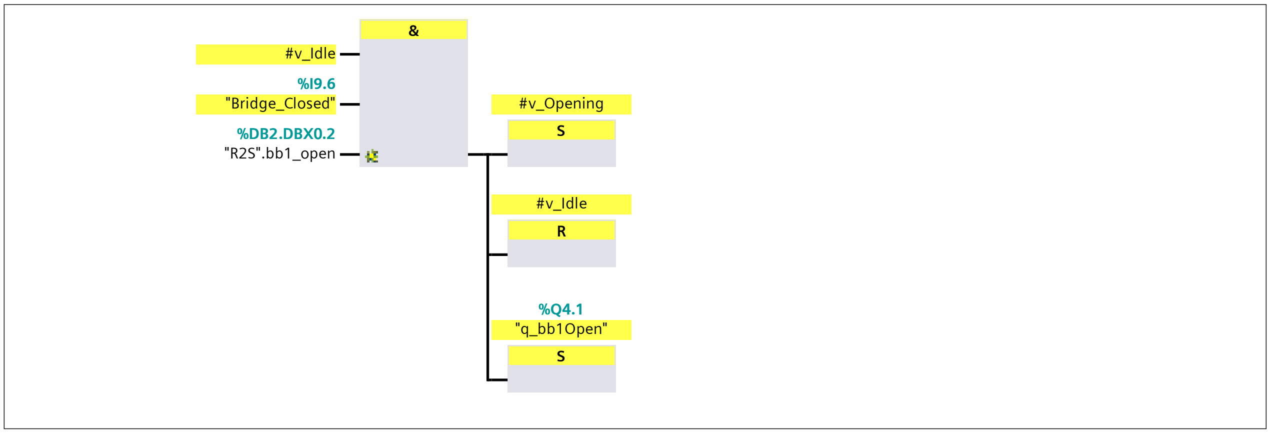
WODES / PLC_1 [CPU 315F-2 PN/DP] / Program blocks

boombarrier1 [FB3]

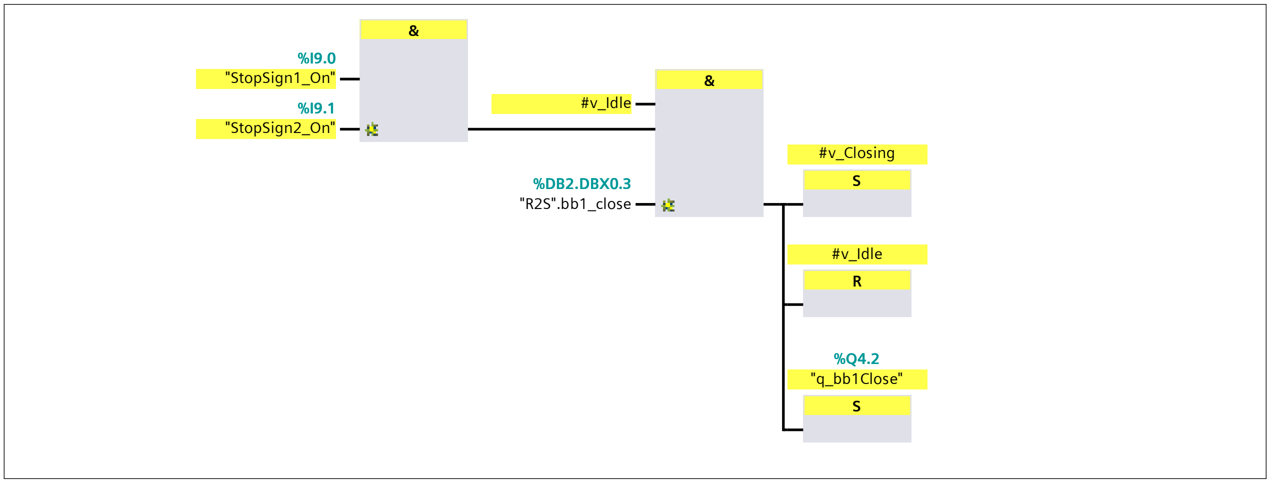
boombarrier1 Properties					
General					
Name	boombarrier1	**Number**	3	**Type**	FB
Language	FBD	**Numbering**	Automatic		
Information					
Title	boombarrier1	**Author**		**Comment**	
Family		**Version**	0.1	**User-defined ID**	

Block_1									
Name	**Data type**	**Offset**	**Default value**	**Accessible from HMI/OPC UA**	**Writable from HMI/OPC UA**	**Visible in HMI engineering**	**Setpoint**	**Supervision**	**Comment**
Input									
Output									
InOut									
▼ Static									
v_Opening	Bool	0.0	false	True	True	True	False		
v_Idle	Bool	0.1	true	True	True	True	False		
v_Closing	Bool	0.2	false	True	True	True	False		
Temp									
Constant									

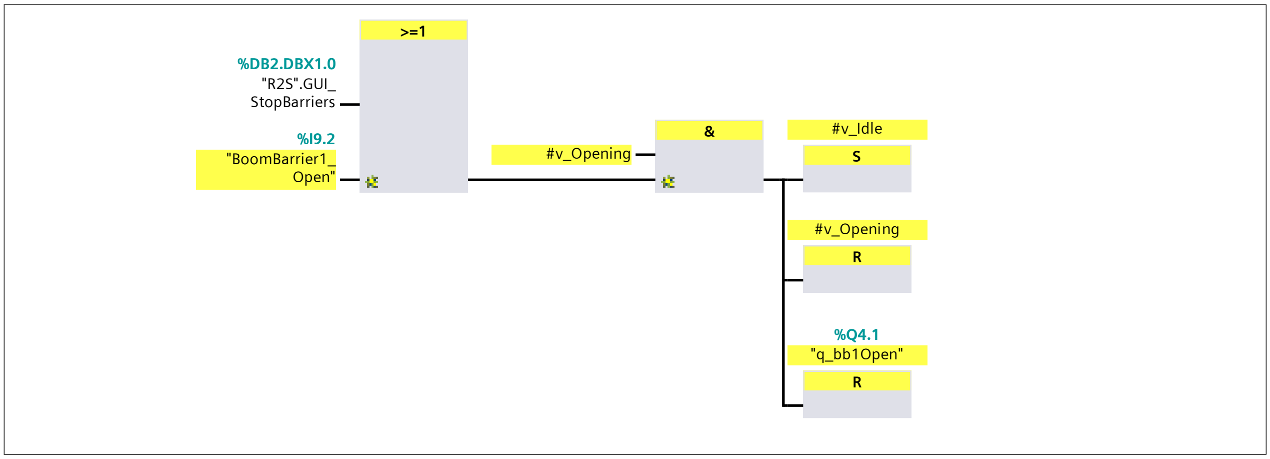
Network 1: open



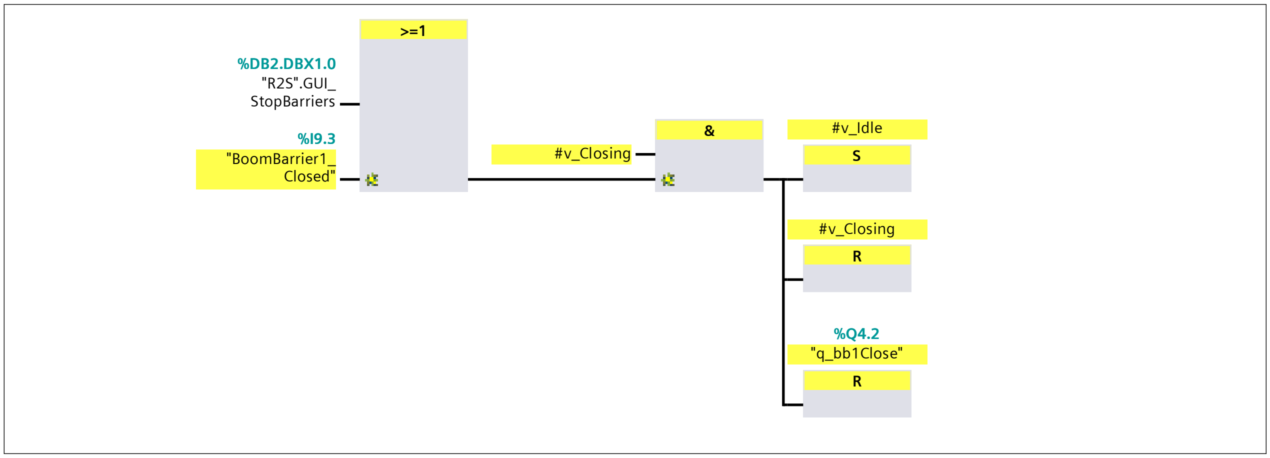
Network 2: close



Network 3: stopOpen



Network 4: stopClose



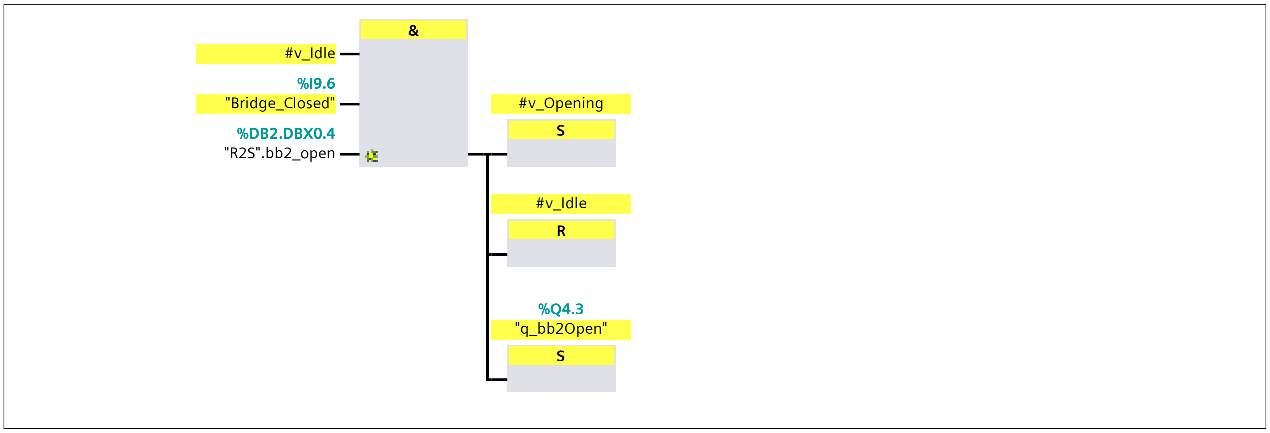
WODES / PLC_1 [CPU 315F-2 PN/DP] / Program blocks

boombarrier2 [FB4]

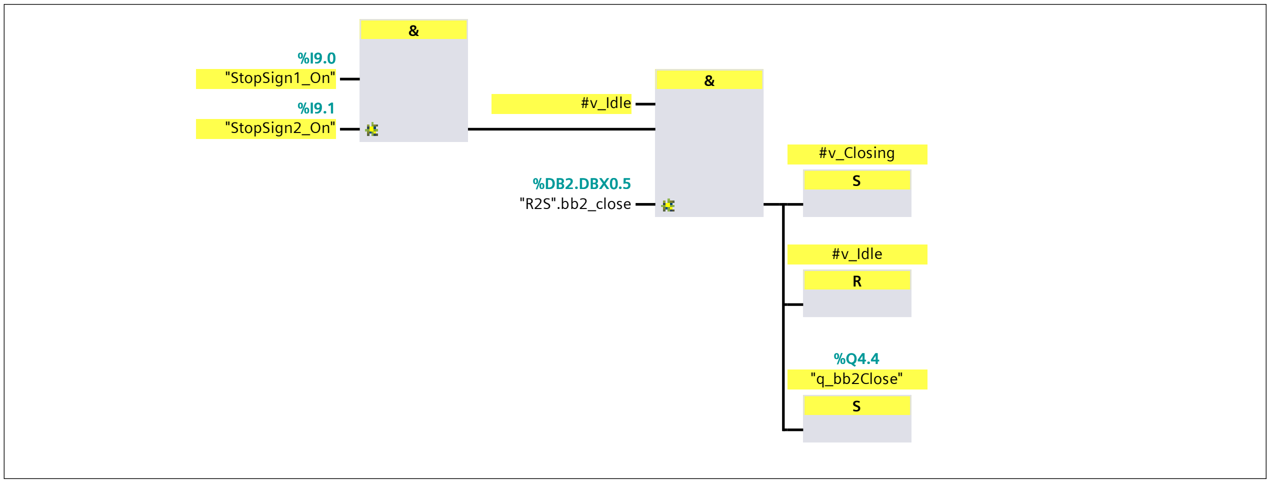
boombarrier2 Properties					
General					
Name	boombarrier2	**Number**	4	**Type**	FB
Language	FBD	**Numbering**	Automatic		
Information					
Title		**Author**		**Comment**	
Family		**Version**	0.1	**User-defined ID**	

boombarrier2									
Name	**Data type**	**Offset**	**Default value**	**Accessible from HMI/OPC UA**	**Writable from HMI/OPC UA**	**Visible in HMI engineering**	**Setpoint**	**Supervision**	**Comment**
Input									
Output									
InOut									
▼ Static									
v_Opening	Bool	0.0	false	True	True	True	False		
v_Idle	Bool	0.1	true	True	True	True	False		
v_Closing	Bool	0.2	false	True	True	True	False		
Temp									
Constant									

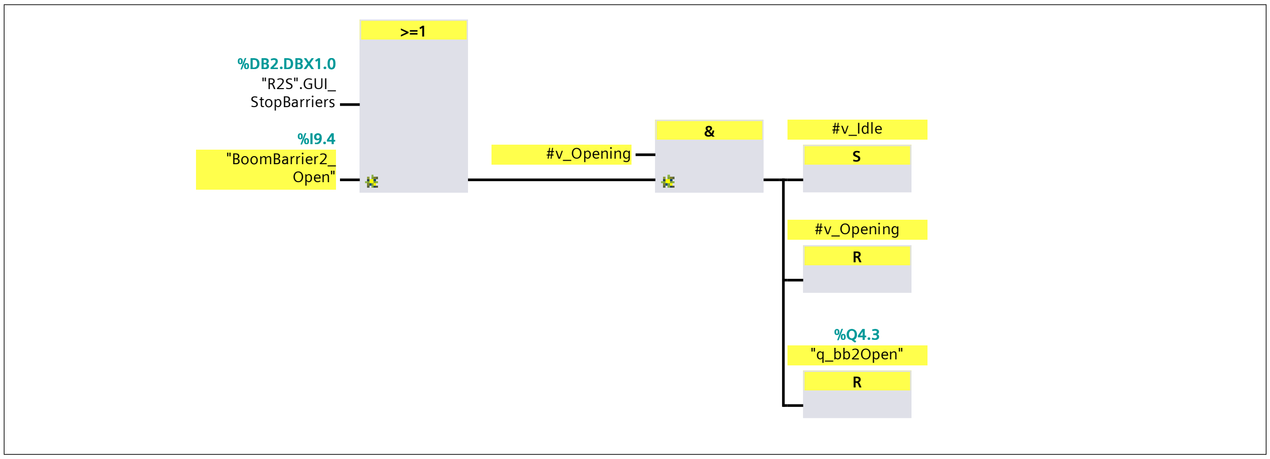
Network 1: open



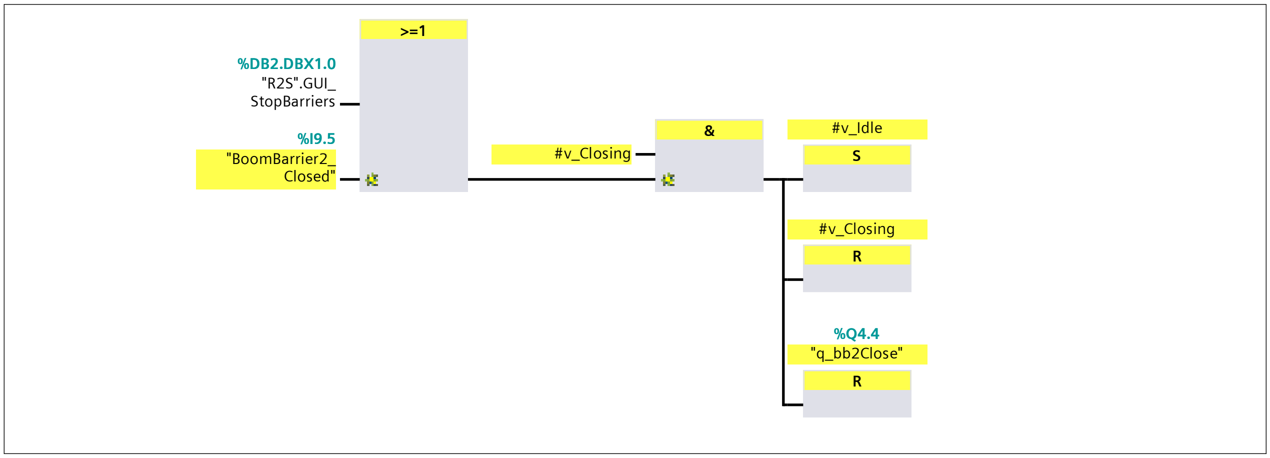
Network 2: close



Network 3: stopOpen



Network 4: stopClose



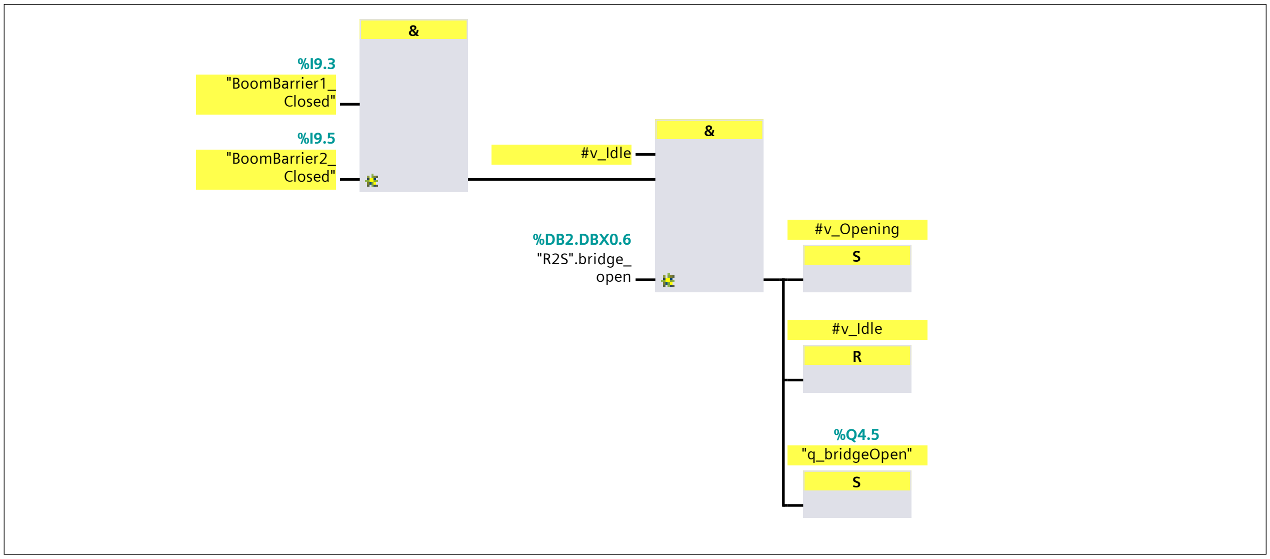
WODES / PLC_1 [CPU 315F-2 PN/DP] / Program blocks

bridge [FB5]

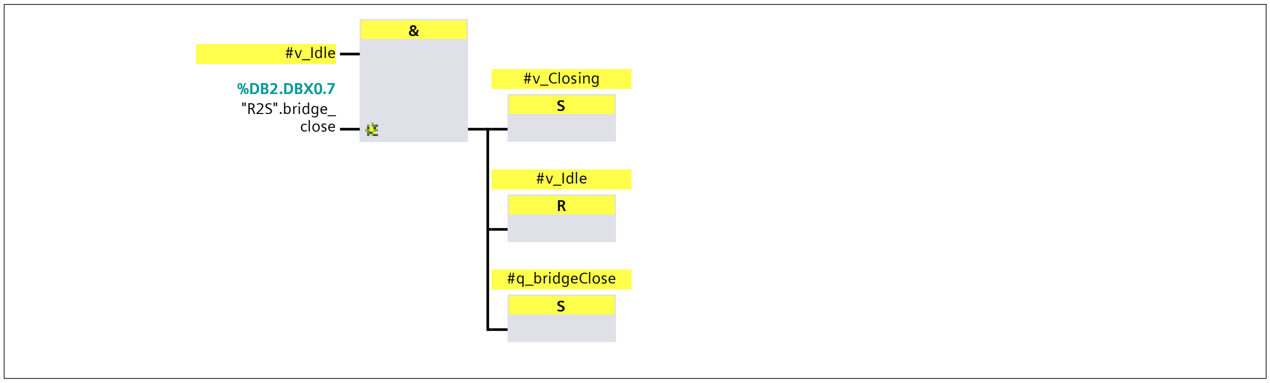
bridge Properties					
General					
Name	bridge	**Number**	5	**Type**	FB
Language	FBD	**Numbering**	Automatic		
Information					
Title		**Author**		**Comment**	
Family		**Version**	0.1	**User-defined ID**	

bridge									
Name	**Data type**	**Offset**	**Default value**	**Accessible from HMI/OPC UA**	**Writable from HMI/OPC UA**	**Visible in HMI engineering**	**Setpoint**	**Supervision**	**Comment**
Input									
Output									
InOut									
▼ Static									
v_Opening	Bool	0.0	false	True	True	True	False		
v_Idle	Bool	0.1	true	True	True	True	False		
v_Closing	Bool	0.2	false	True	True	True	False		
q_bridgeClose	Bool	0.3	false	True	True	True	False		
Temp									
Constant									

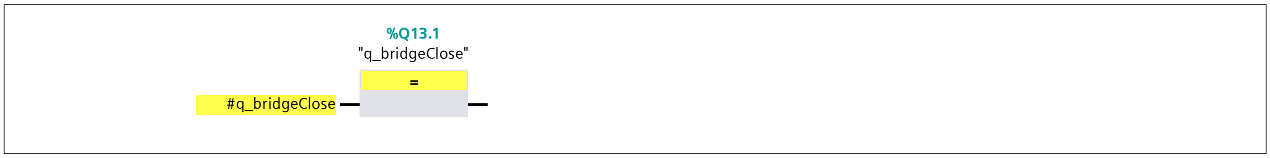
Network 1: open



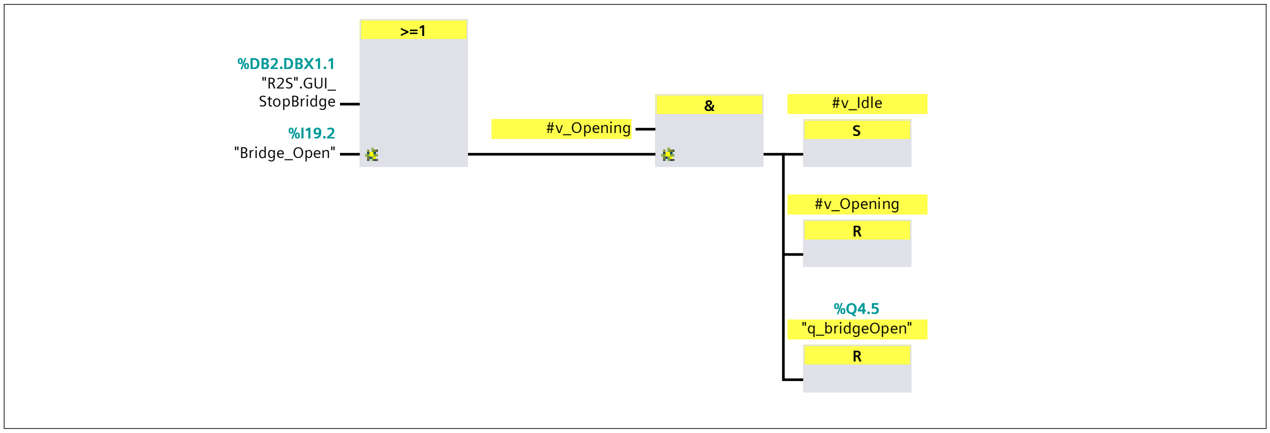
Network 2: close



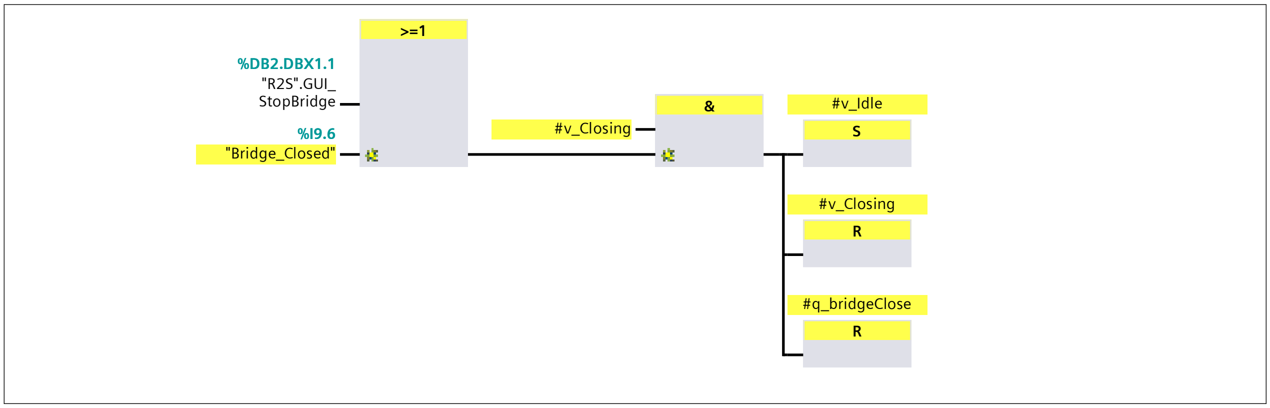
Network 5: qclose



Network 3: stopOpen



Network 4: stopClose


>=1
%DB2.DBX1.1
"R2S".GUI_
StopBridge
%I9.6
"Bridge_Closed"
#v_Closing
&
#v_Idle
S
#v_Closing
R
#q_bridgeClose
R